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THE EVOLUTION OF THE EARTH[1]

I. Earth-Genesis

By Professor THOMAS CHROWDER CHAMBERLIN

THE UNIVERSITY OF CHICAGO

THE evolution of the earth is but the domestic chapter of the evolution of the heavens. In the great volume that records the history of the stellar galaxy no doubt there are a multitude of little chapters of planetary evolution. It is our task merely to tell the story of our own planet. The evolution of other planetary systems may not always have followed the same lines. No doubt many agencies are concerned in the evolution of the bodies that attend the stars. Quite different methods may have given rise to these attendants. It is our task to detail, if we may, the particular way in which our planet and its kindred planets came into being.

The qualities inherited by the earth from the mode of its birth very likely carried into all its subsequent history influences of high potency. Unless we detect the essential nature of these at the start, we will quite surely go astray in the interpretation of the events that followed. It is scarcely less than imperative that we dwell with some care on the initial stages.

Our method must be that of the naturalist—the geo-naturalist, the cosmo-naturalist; it must be an endeavor to find in the features of the earth and of the planetary system the autobiographic story of the planet's experiences recorded automatically in planetary language.

There was a time when mankind very generally was wont to treat with levity the endeavors of geologic pioneers to read the ancient history of the earth from its automatic record. But those days have passed; the intelligent world to-day accepts with confidence the story of the earth's history as it is read in strata, in life relics, in water-marks, in the necks of ancient volcanoes, and in the stumps of vanished mountains. The world recognizes and respects the lithographic story that

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tells—with incompleteness, to be sure, but with great fidelity—the history of the earth reaching back for perhaps a hundred million years.

Back of that, even the scientific world is still wont to regard the story of our planet as falling into obscurity, for the lithographic scriptures cease to be fully legible with the Paleozoic terranes, and with the lowest Archean, the whole lithographic record becomes inaccessible. We are wont to assume that because this lithographic record has failed us, there is no other record to which we may have recourse. But there are dynamic vestiges of creation as well as lithographic vestiges, and some of these dynamic vestiges bear witness to the much earlier stages of terrestrial history, reaching back even to the earth's nativity. We may say with confidence that these dynamic vestiges tell the story of its birth; we may not say with equal confidence that we have read the story aright, or that it can as yet be read aright; we may merely say with confidence that the story is thus recorded. The reading of dynamic records presents inherent difficulties; we are but scantily familiar with such literature; but the record is none the less sure; certain dynamic records are even more instructive than lithographic inscriptions.

Our planetary system records itself as a group of bodies circling about their controlling star, the sun, in ways that are full of meaning. There are singular relationships one to another; there are remarkable symmetries and departures from symmetries; these relationships tell the story of the kinship of the planets to one another, and their kinship to the sun. In some large measure—whether we can yet read it aright or not—they tell the story of the planetary births. They even tell vital facts of planetary history. The harmony in the planetary family is such as to make it quite sure that throughout its whole history it has never been seriously perturbed by external influences. Such are the peculiarities and the symmetries of the planetary organization that it is fairly safe to say that during its existence, be it a hundred million years—or ten hundred million years, if you please—the system has never been so near to another body of stellar massiveness as to suffer serious disturbance of its internal relationships. If the solar system had ever been within a billion miles of another body of the mass of our sun, the record of that approach would appear in the dynamic vestiges of the system as it is seen to-day.

In this record of internal harmony, this record of an undisturbed career, there lies a guiding suggestiveness that may not appear on first statement. The center of the system is moving through space at the present time at about nineteen kilometers per second; around this center, as it speeds through space the members of the planetary family circle in close attendance on their governing star. As a harmonious group they have thus swept a broad path throughout all the history of the system. The immensity of this sweep at once challenges the power of the imagi-

nation to picture such a vastness of space and such an openness of distribution of stars within it as to make possible an undisturbed journey of so broad a system.

So wide deployment of the stellar system implies energies and movements of a stupendous type. These constituted the dynamic environment of the earth's nativity. The nature of these stupendous energies and the laws of these vast activities may serve as our guide in a search for the conditions of planetary birth.

We may at once catch a hint of no little value. The massive center of the solar system is moving among the stars at the notable rate of nineteen kilometers per second; the earth is circling about it at the higher rate of thirty kilometers per second and yet is attending it in its journey through space. The earth pursues a spiral path of notably greater length than the path of the sun. We ourselves on its surface sweep around the earth with its rotation and describe a more tortuous, a longer and a swifter path than the center of the earth itself. The molecules of the atmosphere fly to and fro with prodigious rapidity while they accompany us in our tortuous course; in their still more devious paths they are moving much faster than we. If you will recall the initial lecture of this series by Sir Ernest Rutherford, it will bring to mind particles whose velocities are prodigious, even when compared with the swiftest of the swift celestial movements. Out of this comparative series we may catch a glimpse of the law that the smaller bodies of celestial space move more swiftly than the larger bodies, as a general rule; a law inherent in the nature of the case, a law founded on the natural workings of the principle of the partition of energy.

The suggestions of this law are adverse to those inherited ideas which associate inertness with scattered matter; which assign it the lazy habit of "floating in space," which assume that it may slowly assemble. These seem to be inheritances from the picture of primeval chaos. Quite the contrary, it would seem that the little bodies and the scattered matter are the most active of the active in the celestial world. No vestige of chaotic inertness seems to be found either in observation or in good theory.

The vast deployment of the stars implied by the long swift journey of our system among them teaches us at the same time of the immensity of the celestial energy that actuates the vast moving assemblage. We are accustomed to look to the stars themselves as the great sources of energy —and their radiant output is indeed prodigious—but the motion of the stars themselves is an expression of greater energy than is their radiance, while the deployment of the stars involves potential energies which are a high multiple of both these other great sources combined. And then there are the unmeasured resources of radioactivity.

These general observations are but a means of catching some glimpse

of the environment which encompassed the nativity of the earth and contributed to its endowment. These prodigious sources of energy, the radiant activities, the inertia of stellar movement, the potential energies of deployment, and the occult energies of atomic dissociation combined to endow the earth with those energies that have actuated it during its prolonged history. In the vast openness of heaven, amid its intense activities, and partaking of its prodigious energies, the earth appears to have had its birth.

There are two contrasted types of hypotheses of the origin of the earth and of its kindred planets. The one class have taken for their start the assumption that the parent matter was already widely dispersed in space. They have contented themselves with simply endeavoring to interpret the segregation that followed. They have been content with one half the story. The other class have felt the obligation first to find adequate agencies by which the requisite matter might have been deployed, and then, from that deployment, and in full consistency with it, have endeavored to interpret the mode of its reaggregation into a new system. These hypotheses endeavor to recognize the forerunning destructive factor as well as the sequent constructive factor. They thus try to decipher the whole story; starting from a beginning in conditions such as exist in the heavens to-day, they try to trace the evolution on to an end like that presented by the earth and its kindred as we now find them.

To the first type belongs the most ancient genetic concept that has come down to us, an evolution from primeval chaos. If I have been so fortunate as to impress what seem to me the most essential conditions that dominated the celestial environment at the time of the earth's birth, there will be little need to dwell upon any idea inherited from the ancestral picture of primeval chaos. The ancient idea of chaotic inertness, of mere passive susceptibility of segregation, awaiting endowment with exotic force, seems to have no warrant in anything now observable in the stellar universe. If the picture of primeval chaos were ever true, it would seem that its day must have lain far back of the birthday of the earth.

The hypotheses that have commanded the largest assent during the past century have usually started with assumptions somewhat akin to the ancient concept of chaos, but yet distinctly removed from it by postulating conditions and endowments akin to those supposed to reside in the dispersed states of matter now seen in the heavens. The task that these hypotheses set themselves was the delineation of the course of transformation from a postulated nebulous state into an organized planetary state, a process at once of nebulous partition and of nebulous concentration. The segregative work was assigned chiefly to gravitation; the partitive work, the separation of matter to form the individual

planets, was chiefly assigned to centrifugal action. In the brevity enforced by the limits of the hour, it will be convenient to group all such hypotheses into a centrifugal genus. The essential feature of this genus lay in the assigned tendency of the nebulous matter to concentrate itself until its velocity of rotation set off certain parts which later condensed into planets, planetoids and satellites. To be consistent, every hypothesis belonging to this genus, whatever its special terms, must stand the test of a fair accord with the criteria that inevitably attend the results of centrifugal action. The parts set off by such action should lie somewhat accurately in the plane of the equator of the body that set them off, the sun. The sun itself must retain a rotatory velocity in keeping with its assumed competency to shed matter in this way. How does the centrifugal hypothesis stand these critical tests? The earth is now revolving around the sun at thirty kilometers per second. If it were set off by centrifugal action at this distance from the center of the system, the rim of the rotating mass should have then moved at this notable velocity of eighteen miles per second. When the parent mass shrank to the orbit of the innermost planet, Mercury, it should have had an equatorial velocity of nearly fifty kilometers per second. The rotation should have further increased with further contraction. If the rotation of the sun were competent to cast off masses from its equator with its present dimensions, it should have a velocity of 435 kilometers per second. As a matter of fact, it has a velocity of about two kilometers per second. Here is a grave discrepancy. The sun's equatorial velocity is scarcely a two-hundredth part of what is required to discharge matter centrifugally from its present surface.

The equatorial plane of the sun is inclined to the orbit of the earth; by the hypothesis, the matter of the earth should have been shed quite accurately in the sun's equatorial plane. This plane is also inclined to the orbital planes of each one of the planets. More significant still, it is inclined to the invariable plane of the planetary system which represents the dynamic summation of the planes of all the planets. The inclinations, to be sure, are not great, the earth's orbital plane being inclined 7° 15 to the equatorial plane of the sun; but when the prodigious inertia of the planetary movements is taken into account, even this variation is a notable discrepancy; perhaps it is not a fatal discrepancy in itself, but it adds to the gravity of the great rotational discrepancy. If, as one of the incidents of the generation of the new planetary system, the sun's rotation was reversed, as seems not improbable from the remarkable slowness of the sun's present rotation and the inclination of its axis, its original inclination would be as large as an exacting application of the law of probabilities would demand.

The rotational discrepancies are not confined to the simple facts of slowness and inclination. If the rotational value of the sun were in-

creased by the accession of all the planetary bodies carrying into it all their momentum values, with the consequent acceleration of its velocity, it would still be incompetent to discharge from its surface centrifugally the several planets in their places. The elaborate investigations of Dr. Moulton have placed this upon a specific and invulnerable basis. The discrepancies disclosed at the several stages of the postulated evolution range from disparities of 140:1 up to 1,800:1.

So also, there are discrepancies between the masses of the several planets and the momenta they should carry under a systematic process of centrifugal separation. If the postulated nebula at the time it was, by hypothesis, preparing to shed the great planet Jupiter, be restored, every layman more or less familiar with mechanical laws may estimate for himself, in some rough way, at least, the relative value of the rotatory momentum carried by the whole body and by an equatorial rim of one-thousandth part of the body, respectively, making all due allowance for the fact that the momentum of the outer part has a higher value than that of any similar part within, not only because it moves faster, but also because it moves on a longer arm. The mass of Jupiter and his moons taken together is somewhat less than a thousandth part of the mass of the postulated nebula at the time the separation of the supposed Jovian ring took place. Now if one has formed such a rough estimate one will be ready to appreciate the meaning of the fact that Jupiter actually carries more than 96 per cent. of the total value of the rotatory momentum of the nebula at the time of its assigned partition, while the 999 parts left behind by hypothesis carry only the remaining four per cent. The sun itself, massive as it is, now carries only about two per cent. of the momentum values of the whole planetary system, while 98 per cent. is carried in the attendant bodies, and yet the total mass of these attendant bodies is only about 1/745 of the solar mass. That such are not the proportions that would arise from a systematic separation of the planets from a parent nebula by centrifugal action is quite clear even on simple inspection; it may be confirmed by computation, which shows that there are even more remarkable discrepancies in the cases of some other planets.

A very slight portion of these discrepancies may be referred to tidal action, but the computations of Sir George Darwin show that this amelioration is extremely trivial.

There are other striking discrepancies. If the centrifugal mode of planetary separation obtained in the solar system, the planets should take less time to rotate upon their axes than the satellites to swing around them at some distance, and yet Phobos, the little inner satellite of Mars, sweeps around the planet about three times while the planet rolls around once. Moulton has pointed out, also, that the little bodies that make up the inner side of the inner ring of Saturn circle around

that planet about twice while the planet rotates once. If tidal friction is appealed to as a means of bringing these into consistency, it is found available, as Dr. Moulton has shown, only if one of these cases is three thousand times as old as the other.

It is a necessary inference that satellites, shed centrifugally, should rotate in the same direction as the planet from which they were cast off; and yet it has recently been discovered that one of the satellites of Saturn rotates in a direction contrary to the planet and its eight other satellites. Still more recently it has been discovered that two of the satellites of Jupiter disregard the family habit in a similar fashion. This behavior seems fatally inconsistent with a centrifugal origin.

If we turn to the heavens for their testimony, none of the many thousands of nebulæ show a concentric system of symmetrical circular rings, fulfilling the postulates of the hypothesis. Figs. 1, 2, 3 and 4 are introduced to show such imperfect degrees of approach to conformity with this hypothesis as are presented.

The foregoing formidable series of grave discrepancies, conjoined with this lack of convincing illustrations of centrifugal evolution in progress among the many thousands of nebulæ now known, seem to require us to set aside the whole centrifugal genus of genetic hypotheses, including as its foremost exponent the venerable hypothesis of Laplace—so far, at least, as the genesis of our planetary system is concerned. We may not do this without a recognition of the profound stimulus that these hypotheses have given to inquiry into the origin of the solar system during the past century.

The hypotheses that have commonly been called meteoritic have usually been built up on a structural or textural basis rather than a dynamic one. They have been rather theories of the constitution of nebulæ than theories of the origin of the earth. They have not been worked out into the specific details of separation and followed out through all concentrative processes down to the stages of the existing planets. They do not, therefore, lend themselves readily to brief discussion. As theories of the constitution of nebulæ they have not been sustained by progressive inquiry.

In so far as supposed meteoritic assemblages constitute swarms and are actuated by collision and rebound in quasi-gaseous fashion, as developed by Sir George Darwin, they are subject to the grave difficulties we have just cited against the more familiar gaseous forms of the centrifugal genus.

In so far as the postulated meteorites are supposed to pursue individual orbits, a series of difficulties of a different type are encountered. The precise form of these difficulties varies according to the specific form given the hypothesis. If the planes of revolution of the individual meteorites lie in various directions, as is natural in a heterogeneous

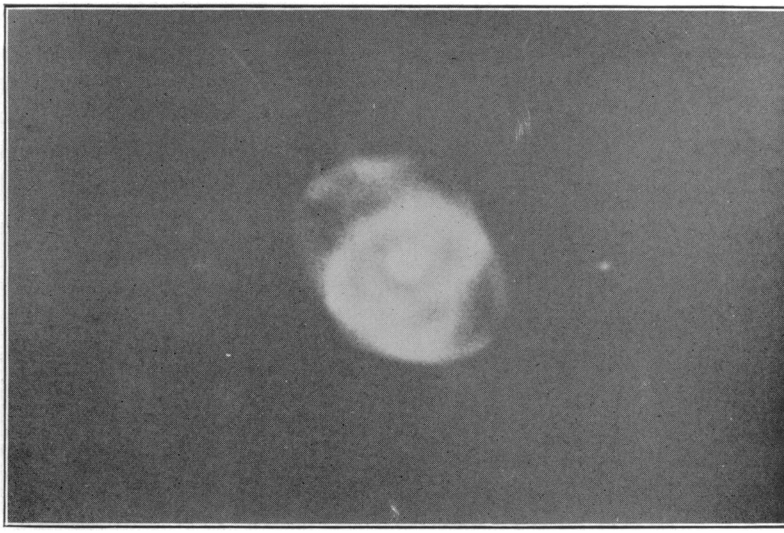


FIG. 1. NEBULA N. G. C. 6543, DRACO, PLANETARY. Spectrum, bright lines on a continuous background. Photo from Mt. Wilson Solar Observatory. Note apparent absence of gradation and hydrostatic support.

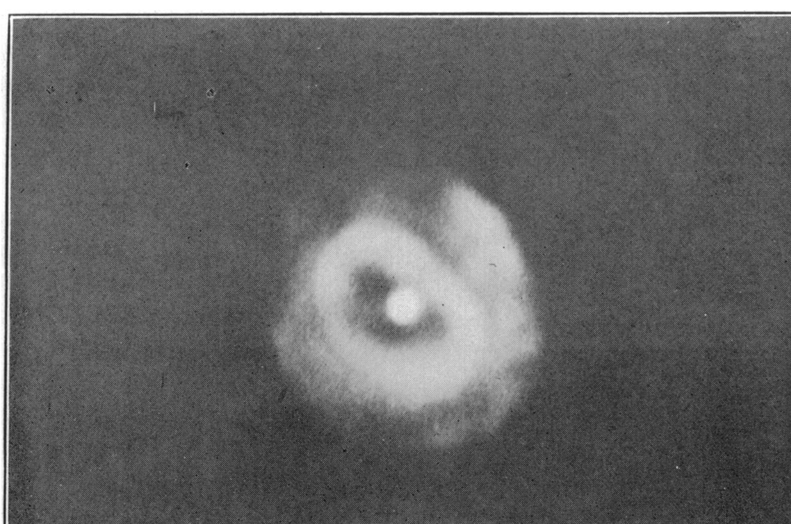


FIG. 2. NEBULA N. G. C. 7662 (H IV 18). The Andromeda planetary. Photo from Mt. Wilson Solar Observatory.

assemblage, the concentration tends toward globularity, whereas our planetary system is pronouncedly discoidal. The difficulties of asssigning a globular cluster of revolving meteorites such a system of dynamics as shall cause them to evolve naturally into a highly discoidal system of revolutions, with 98 per cent. of the moment of momentum concentrated

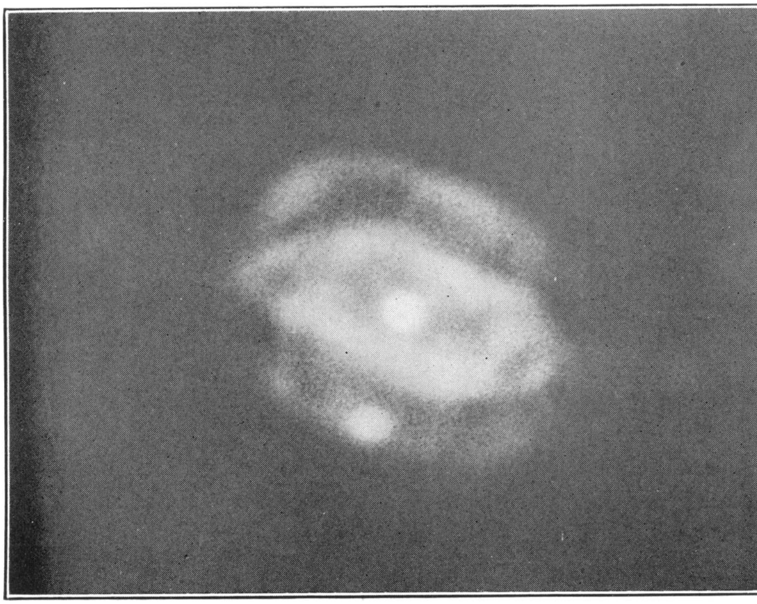


FIG. 3. NEBULA N. G. C. 7009. "Saturnian" planetary. Note the faint "ansæ" in the extrusion of the major axis. Photo from Mt. Wilson Solar Observatory.

FIG. 4. NEBULA N. G. C. 7217 (H II 207). Note the knotted structure and the faint oblique spiraloid tracts. Photo from Mt. Wilson Solar Observatory.

in 1/745 of the outlying material, are very grave. The difficulties of aggregating sparsely scattered revolutionary meteorites, highly endowed

with momentum, into a few large planets, without special collecting centers, are also grave.

There is an inherent difficulty in assigning any competent aggregative tendency to meteorites as such, if we may judge from the dynamics of those within reach of observation. With their observed velocities their momentum is extremely high relative to their attractive power. The individual attractive power of an average meteorite is almost immeasurably feeble. The sum total of attraction of a great swarm of meteorites, if such exist, might indeed be high, but it is an attraction toward the common center, not toward outlying points where the planets must grow up. In and of themselves, meteorites are controlled by a dispersive rather than a concentrative tendency. It is only by starting with the *assumption* of an enormous assemblage whose initial gravity is sufficient to hold the individual meteorites under control, that it is possible to proceed rationally at all, and then the concentration is presumably toward the common center of gravity and not toward outlying planetary centers.

If the difficulties of a definite segregation into a few large planets revolving in a sharply appressed disk have been met at all under the meteoric hypothesis, it has been rather by a tacit assumption of the appropriate concentrations than by the assignment of specific reasons for such an aggregation. But concentration must already have gone far before it comes to have much aggregating force. Even the full-grown earth has relatively little power to swerve the meteorites from their paths. It collects them, to a trivial extent, chiefly because it lies in their path, not because it is a controlling center for their aggregation; their velocities are too great for effective concentration. The earth can not control a velocity so great as seven miles per second, while the average velocity of meteorites relative to the earth seems to be three or four times that. In the absence of effective collecting centers the mutual collisions of meteorites moving at observed rates would result in fragmentation and still more minute dispersion. This is, with little doubt, the reason why most meteorites are so small, and why their habits are so pronouncedly dispersive. They are food for the scant feeding of massive bodies already formed, but they are deficient in formative power themselves.

The foregoing are at best but half-hypotheses. They start with assumptions of certain kinds of nebulæ already formed and merely try to trace the evolution of these into a planetary system. The more complete classes of genetic hypotheses endeavor to go back to the beginning of the dispersion that prepared the way for reaggregation into a new system. They thus try to tell the whole story. This broader endeavor early found a representative in a theory quite as venerable as the hypotheses of Kant or Laplace, but unfortunately it is not worthy of serious consideration as a specific explanation of the origin of our planetary system. It is

merely representative. More than a century ago the naturalist Buffon suggested that a comet might have collided with the edge of the sun and have driven off sufficient matter to form the planets. While this is obviously an untenable view, the dynamic concept of a glancing collision of one form or another between two bodies has been the basis of a series of hypotheses which may be grouped together as a collisional genus. This genus avoids some of the fundamental difficulties that lie so gravely against the preceding hypotheses. A collisional impact might leave the rotation of the sun as slow as it actually is. The collisional effect might obviously be accelerative or retardative according to the mode of stroke. By hypothesis the sun might have any possible velocity of rotation. The sun's axis might lie in any direction. So also, the matter driven from the edge of the sun might, by hypothesis, have all the momentum that any of the members of the planetary system possesses in perfect consistency with the sun's slow rotation and its oblique axis. It is no small merit in this genus of hypotheses to escape the fundamental difficulties of rotation and momentum that have proved to be so grave in the centrifugal genus.

But the collisional genus encounters, in its turn, certain formidable difficulties. In the first place, the mass of the sun, just before the collision, could not well have been less than it is now, and hence an approximate velocity may be assigned the collision. A body coming from without the sun's sphere of control would, neglecting any pre-existent velocity of its own, strike the edge of the sun at a velocity of the order of 600 kilometers per second, due to the sun's powerful attraction. If the body fell merely from some outer part of the sun's sphere of control, it still would have a velocity of a very high order of magnitude. If the sun's volume were larger at the time and the stroke took place farther from the sun's center of gravity, the velocity would indeed be lower; but still it would be high under any reasonable hypothesis of this type. To follow logically the consequences of such a glancing collision it is necessary to give due weight to the violence of the encounter which these high velocities imply. The normal effect of such collisions would be a radial dispersion of both the striking and struck matter diverging from the point of encounter in various forward directions, except perhaps in such as were protected by the undispersed portions of the sun and of the colliding body; in other words, there should be a more or less fan-like radiation, with perhaps a truncated side representing the protecting effects. The two great nebulæ of Orion (Fig. 5) seem, in some measure, at least, to fulfil these specifications. Normally the dispersion, under conditions so violent, would be extremely high. Nuclei for gathering together the dispersed matter into a few great planets would seem to be counterindicated by this, and the conditions for aggregation in any planetary form would apparently have been unpropitious.

FIG. 5. THE GREAT NEBULA OF ORION AND ITS COMPANION NEBULA. Bright line spectrum. Note evidences of special structure, absence of graded continuity and of hydrostatic support, in both nebulæ. Photo from Yerkes Observatory.

But there is a more radical difficulty. Under the laws of mechanics, the dispersed matter driven off by the collision, if it were kept under control by the sun at all, must return to the point of collision and there be subject to a second collision, with a similar necessity of return and so on. Even if by some perturbation in the course of their outward or returning path, some of the dispersed matter were driven into new paths so that they escaped recollision, they must probably have assumed very eccentric and diverse orbits. The orbits of the planets do not present the characteristics that seem derivable from such sources. The orbits of all the planetary bodies are sub-circular, and they are distributed about

one another with a certain measure of symmetry that does not seem to be a normal product of such a marked asymmetry as would necessarily arise under the collisional hypothesis.

Thus this genus of hypotheses—whatever specific forms may be given the individual hypotheses under it—seems to have but a scant basis of acceptability. Without much question collisions occur in the heavens and evolutions must arise from the products of such encounters, and so the theory has its place in a general study of the evolution of the heavens. But grave difficulties lie in the way of supposing that a solar collision gave birth to our planetary system.

These four types of hypotheses, the chaotic, the centrifugal, the meteoritic, and the collisional, embrace essentially all that commanded much attention during the past century. Of these it is perhaps safe to say that the centrifugal genus, especially as represented by the Laplacian hypothesis, commanded more adherence than all the others combined.

There remains, however, another possibility, less obtrusive in its nature than any of these. For this reason perhaps it was more tardy in receiving consideration. It centers on *dynamic encounter,* that is, the dynamic effect which arises from the close approach of massive bodies without bodily collision. Its effects have certain of the qualities that arise from bodily collision but they are free from certain other qualities that give rise to grave difficulties in their application to our planetary system. While thus related to collision, dynamic encounter is radically distinguished from it. The approach is close only in an astronomical sense. It may range from the mere escape from collision up to a few millions, a few hundred millions, or a few billions of kilometers. The encounter is purely a dynamic one; it is an interpenetration of spheres of gravitative influence involving a contest for gravitative control.

If a star were alone in space it would be surrounded by an illimitable sphere of gravitative influence, strong near the star but declining rapidly as distance increased, yet never entirely disappearing, theoretically at least, within the bounds of space. If a second star were introduced at any point in space, the new gravitative influence would interpenetrate the previous sphere of influence; there would be both conflict and coordination of influence; the two stars would divide the previous sphere of control of the single star, each having its own sphere of dominance. If a multitude of stars occupy space—the actual case—their gravitative influences interpenetrate in a most intricate way, and yet about each star there remains a space within which its gravitative influence is greater than that of its rivals. Each star has its sphere of control; as does also each planet, planetoid and satellite.

Now it is to this conflict and coordination of stellar attractions that the genesis of the dominant class of nebulæ, the spiral, is assigned. It

is to the evolution of a spiral nebula that the genesis of our planetary system is assigned.

Many years ago Roche showed by mathematical analysis that if a satellite be made to approach its primary on an in-running spiral, it will not retain its integrity until it reaches the surface of the primary but will be torn into fragments at a point 2.44 times the radius of the primary, provided the two bodies are homogeneous in density and all internal forces except gravity are neglected. If the density increases toward the center, the limit is larger. The Roche limit for the earth is about 18,000 kilometers; if the moon were to circle down toward the earth, it would be torn into fragments at about 11,000 miles from the earth's center. In being thus disrupted it would probably take on a form analogous to the fragmental clusters that are thought to form the heads of comets. The Roche principle with proper modifications is applicable to any celestial body approaching another on a curved path. If such approaching body has been greatly compressed previously by its own gravity, its internal elastic stress may greatly exceed its cohesion. In gaseous bodies, indeed, cohesion may be said not only to be absent, but to be replaced by repellancy which is only kept under control by the bodies' gravity. If the approaching bodies are great globes of gas, such as are the stars, and if they are subject also to powerful eruptive action, as is our sun, extraordinary effects may arise when a close swift approach is made on a more or less sharp curve, as such approaches always are.

Now imagine a star passing close to another star or massive body, pursuing necessarily a rather sharp curve at its point of closest approach and moving inevitably at very high speed; picture the enormous concentration of energy within such star arising from its molecular activity under its high gravitative compression; add to the picture the inherent eruptive tendencies that arise from this, if it belongs to the type of our sun, and it will furnish the working conditions of the case. Now imagine the interpenetration of the gravitative influences as the two bodies approach one another. Particularly note the way in which the gravity of the massive body penetrates, modifies and even neutralizes the gravitative control of the lesser body over its own substance, the force that had concentrated it into a globular form and strongly compressed it, and the picture will give the working elements for a concept of the prodigious eruptive and dispersive effects that will attend so simple an incident as a close approach. It is easiest to follow a case in which one body is much more massive than the other and is assumed to be so solid and non-explosive as to be little affected, so that the main response is limited to the minor explosive body. The action will be of the tidal type and follow tidal principles; indeed, it will be an extraordinary modification of a tidal process. Under such tidal action the star first becomes

elongated toward the passing body. The eruptions are then concentrated in the tidal cones. The ejections are shot toward and from the controlling body. The dispersive action constantly lies in the line of readjusted attractions between the centers of the two bodies. This line is constantly shifting its position; at the critical stage it is shifting rapidly; but this shift must always be in the plane of movement of the controlling body. It may be helpful to picture the elongated erupting star as a Janus-faced ordnance firing gaseous bolts fore and aft as it swings swiftly about its massive neighbor. The chains of missiles thus shot in opposite directions during the whirl naturally take on the form of two spiral curves as illustrated in Fig. 6. The two-armed feature of the

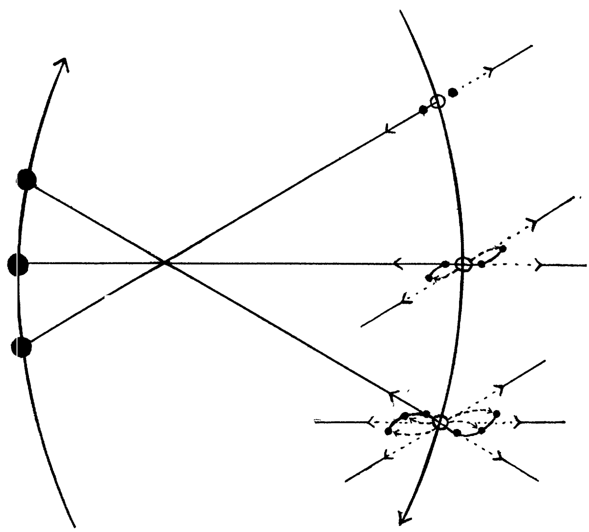


FIG. 6. DIAGRAM ILLUSTRATING A HYPOTHETICAL MODE OF FORMATION OF A SPIRAL NEBULA.

spiral which results is amply exemplified in the spiral nebulæ. A star with an inherent explosive habit passing near a massive body thus, by interpretation, is converted into a spiral nebula.

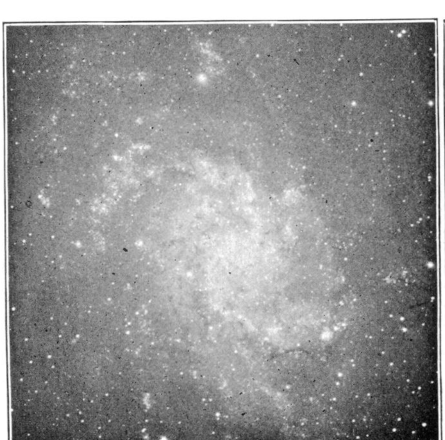
How large a portion of a given star will be shot forth into spiral arms depends on the closeness of approach, the elastic compression of the star, the massiveness of the passing body, and other factors. If the star passes within the Roche limit of the more massive body it may, theoretically at least, be entirely deployed into spiral arms, leaving little or no nucleus behind. If the approach be less near, the residual nucleus will be correspondingly larger. A series may thus be formed which grades from the most dispersed forms in which spiral arms preponderate with almost no nucleus, up through spirals with greater and greater

1. M 51 Can. Ven. = N. G. C. 3572–3574.

2. M 101 Urs. Maj. = N. G. C. 3770–3771.

3. M 74 Piscium = N. G. C. 372.

4. H IV 76 Cephei = N. G. C. 4594.



5. H 33 Trianguli = N. G. C. 352.

6. H I 53 Pegasi and her nebula.

PLATE I. SPIRAL NEBULÆ.

nuclei and less and less dispersed matter, ending in those in which only a minute fraction of star substance was drawn out into spiral arms. As already noted, these arms or clusters of arms start at opposite sides of the nucleus and swing out in opposite directions with curvatures in the same sense. This singular feature is seen to be very persistent in the many thousands of spiral nebulæ in the heavens and may well be regarded as highly significant of the process that gave rise to them.

It is worth while to note that though the degree of dispersion of a star into a spiral nebula may reach even to the essential deployment of the whole star, in certain cases, it is not violently catastrophic in any such degree as follows actual collision. It is partitive rather than extremely dispersive and dissociative. The disruption takes place by a

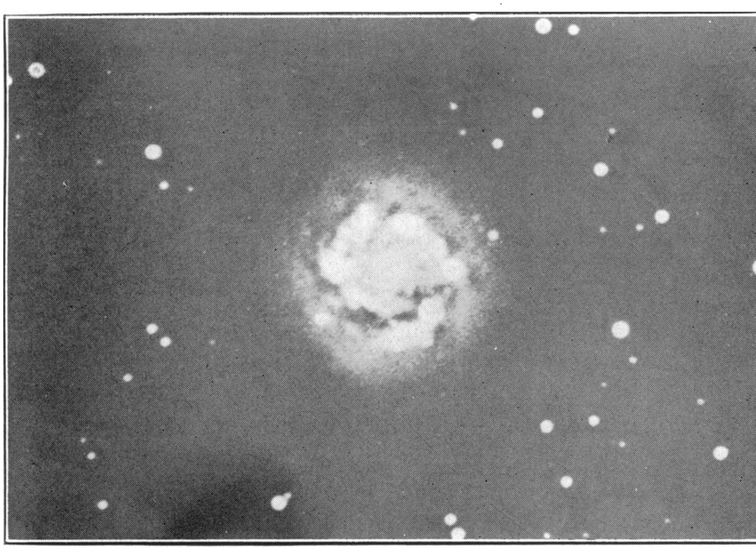


FIG. 7. A SPIRAL NEBULA WITH NEARLY CIRCULAR OUTLINE AND RELATIVELY FEW LARGE KNOTS. N. G. C. 278. Photo from Mt. Wilson Solar Observatory.

series of gas-bolts shot out in succession. The larger of these gas-bolts are supposed to retain mass enough, and hence self-gravity enough, to hold themselves together and so to constitute the nuclei to which the more scattered matter gathers to form the planets, planetoids and satellites into which the nebula later evolves. These bolts shot out by the successive pulsations of the eruptive action form into the knots that so distinctively characterize the spiral nebulæ.

With extreme cases of approach within the Roche limit, and with very close approaches generally which give rise to highly deployed nebulæ, we have nothing to do, except by way of illustration, in our search for the genesis of our planetary family. To fit this case, our sun is sup-

posed to have shot forth bolts to the amount of only 1/745 of its mass to form the members of the planetary family. No doubt some additional matter was involved, but even when large allowance is made for such matter as may have been projected outward and yet returned to the sun, and for such other matter as was possibly shot so far out as to be drawn away by the passing star, and for some that may have been thrown beyond the control of either body, the fraction of the solar mass required to meet the demands of the case still remains very small. There is no reason to suppose that the sun's career as a star was radically affected. The approach was probably a rather distant one, in this particular case.

When the multitude of the heavenly host is considered, and the various directions and speeds of their motions are noted, the event to which the origin of the parent nebula of our planetary system is assigned must be regarded as one of the simplest and most inevitable that could well be named. There is little ground for doubt that actual collisions occasionally occur. There are six or eight chances that a star will pass through even the Roche limit of another star to one that it will collide with it. The chances that a star or massive dark body will pass near enough to an eruptive star to give rise to effective projections from its tidal cones, rise to very much higher order. Here again, the tenor of observed facts tallies with the nature of the theory offered, for the spiral nebulæ are many times more numerous than any other class.

Let us follow a little more closely the assigned method of evolution of the little spiral nebula that is supposed to have grown into our planetary system.

When the passing star that incited the nebular deployment made its approach, its differential pull drew forth tidal "bulges" on the opposite sides of the sun. These were really cones rather than the broad bulges usually pictured, but superposed as they were upon a spheroidal surface they appeared as merely bulges, as commonly represented. The term cone, however, better represents their dynamic function. At the same time that the cones were drawn out on the line joining the sun and the star, a belt of inward pressure was brought into play at right angles to them. The joint effect of the protrusion of the cones and the compression at right angles to them was a concentration of the sun's eruptive tendencies into the cones. At the same time, the eruptive function was powerfully stimulated. As a result, the sun shot out gas-bolts from the quasi-volcanic cones whose mass was much greater and whose velocity was much higher than that of the eruptive prominences which are now shot forth at short intervals in a more sporadic way even in the absence of any such special outside stimulus or internal concentration. In the absence of a passing star these eruptions of course fall back to the sun. But if a bolt were shot far out toward the passing star, it

would be drawn forward by it. If only slightly drawn forward, it would return to the sun, but would carry back with it such transverse momentum as it had acquired. This would affect the rotation of the sun. The ejection on the opposite side of the sun would act in a similar way in accordance with well-known tidal principles. If the bolt were pulled forward sufficiently far it would fail to strike the sun on its return and would fall into an orbit about it. If the pull were effective enough, the projectile would not return at all to the sun but swing into an orbit about the passing star. If the respective pulls of the star and the sun against one another happened to be properly balanced, they would throw the projectile out of the control of both and it would go off into space and probably pass under the control of some other star.

Dr. Moulton traced out mathematically the courses of such projectiles in nearly half a hundred selected cases and found the process competent to give a wide range of results. In the first ten cases tried all of the contingencies just named were realized. The eccentricities of the orbits were often large, but the range of variation was such that when the many small bodies of the nebula were gathered into a planet the combined orbit would approach a subcircular form. The potency of the mechanism was found unexpectedly high; its efficiency as a pa·titive and distributive agency proved to be quite beyond anticipation.

It need not be urged that the solar eruptions under these conditions would be pulsatory, or that the gas-bolts would be subject to sub-fracturing and to the wide scattering of a part of their material. From such actions would arise "knots" of different orders and highly scattered "haze," the constituents which make up practically all spiral nebulæ.

This, then, is the mechanism to which is referred the origin of our planetary system. It is of vital moment to note just how those critical features in our planetary system that seemed to offer so serious objections to the older hypotheses, are met under this interpretation. The gas-bolts shot out from the sun were, under the assigned mechanism, given transverse momentum by the attraction of the passing star. Thus the planets into which they were collected received their high endowments of moment of momentum, endowments that were proportionately of a much higher order than that of the sun. Some endowment was indeed received by the sun from the same source through the projectiles that fell back to it. The ancestral rotation of the sun is supposed to have been nearly opposite to its present rotation. The contribution of momentum from projectiles falling back first neutralized the sun's rotatory force and then reversed it, finally leaving it with the very slow rotation and slight obliquity it now has. As all the projected matter was shot either toward or from the passing star and was drawn forward in the direction of its movement, all the nebular orbits were in nearly

the same plane, and the nearly perfect disk of the final system was inevitable. Thus are explained the most radical features. The many other peculiarities of the system grew up as mechanical necessities in the subsequent processes of organization. Given a series of primary knots, the heads of the main gas-bolts of the more effective eruptions, attended by many sub-knots, fragments torn from these in the eruption, attended also by innumerable scattered particles ranging from molecules upwards, all thrown into elliptical orbits of varying eccentricities and slight deviations of plane, and the laws of mechanical aggregation did the rest. The primary knots were the predetermined nuclei of the planets. A multitude of lesser knots formed the nuclei of the planetoids. The secondary knots formed the nuclei of the satellites, while the highly scattered material of the haze was collected into the various nuclei and constituted the food for their growth.

Time forbids us to try to follow out the details. Though the scattered matter was originally molecular, it was neither gaseous nor meteoritic in any strict sense of these terms. It consisted of particles thrown into individual orbits of a common type moving in the same direction about the sun. The integers were thus from the outset of the dynamic nature of minute planets. To emphasize this radical feature they have been called planetesimals. The term embodies the soul of the hypothesis and suggests the dynamics that actuated the later evolution.

This evolution consisted of the natural and inevitable gathering of these planetesimals into the nebular knots serving as nuclei of growth forming ultimately planets, planetoids and satellites. The crossing of the initial orbits and the precessions and perturbations that inevitably arose from the interaction of various parts of the nebula, were the chief agencies in facilitating a gradual organization of the intertangled planetesimal system of elliptical orbits into the simpler and more harmonious sub-circular orbits of the present planets.

In the absence of time to delineate more fully this evolution, we may perhaps be pardoned an expression of the conviction that in the natural course of such evolution the many special features of the planetary system, not excepting its seemingly strange anomalies of rotation and revolution, find satisfactory explanation.[2]

Our special picture of the genesis of our planet, then, is that of an earth growing up about a nebulous "knot" through the rather slow accession of planetesimals, and taking on its mature form by gradual stages under general influences not radically different from those that presided over its later history, save in the gradual diminution of its rate of growth. Some of the salient features of this growth, some of the configurations that were acquired, and some of the dominant processes

[2] A fuller exposition of the hypothesis will appear in "The Origin of the Earth," a book about to issue from The University of Chicago Press.

upon which the planet entered, at maturity, will be the subject of our second lecture.

In a closing word, may I invite attention again to the essential simplicity of the assigned process of rejuvenation by which the sun gave birth to its present planetary family. It involves no postulate of general destruction and re-creation. There is no appeal indeed to any event that may properly be regarded as other than in the natural course of astronomic events. It is merely postulated that one of the simplest and most inevitable of astronomic events stimulated a partial deployment of the sun and gave birth to our modest little planet. The genesis of a planetary family was perhaps quite as much in the natural order of things in the heavens as was the initiation of a biological family in the course of terrestrial history.